DOCUMENTS EXPEDITING PROJECT

[COMMITTEE PRINT]

SPACE PROPULSION

REPORT

OF THE

COMMITTEE ON SCIENCE AND ASTRONAUTICS

U.S. HOUSE OF REPRESENTATIVES

EIGHTY-SIXTH CONGRESS

FIRST SESSION

[No. 26]

AUGUST 6, 1959

Printed for the use of the Committee on Science and Astronautics

---

UNITED STATES

GOVERNMENT PRINTING OFFICE

44005 WASHINGTON : 1959

COMMITTEE ON SCIENCE AND ASTRONAUTICS

OVERTON BROOKS, Louisiana, *Chairman*

JOHN W. McCORMACK, Massachusetts
GEORGE P. MILLER, California
OLIN E. TEAGUE, Texas
VICTOR L. ANFUSO, New York
B. F. SISK, California
ERWIN MITCHELL, Georgia
JAMES M. QUIGLEY, Pennsylvania
DAVID M. HALL, North Carolina
LEONARD G. WOLF, Iowa
JOSEPH E. KARTH, Minnesota
KEN HECHLER, West Virginia
EMILIO Q. DADDARIO, Connecticut
WALTER H. MOELLER, Ohio
DAVID S. KING, Utah
J. EDWARD ROUSH, Indiana

JOSEPH W. MARTIN, JR., Massachusetts
JAMES G. FULTON, Pennsylvania
GORDON L. McDONOUGH, California
J. EDGAR CHENOWETH, Colorado
FRANK C. OSMERS, JR., New Jersey
WILLIAM K. VAN PELT, Wisconsin
A. D. BAUMHART, JR., Ohio
PERKINS BASS, New Hampshire
R. WALTER RIEHLMAN, New York

CHARLES F. DUCANDER, *Executive Director and Chief Counsel*
DR. CHARLES S. SHELDON II, *Technical Director*
SPENCER M. BERESFORD, *Special Counsel*
PHILIP B. YEAGER, *Special Consultant*
JOHN A. CARSTARPHEN, Jr., *Counsel*
RICHARD P. HINES, *Staff Consultant*
LT. COL. PAUL B. SCHUPPENER, *Staff Consultant*
RAYMOND WILCOVE, *Staff Consultant*

LETTER OF TRANSMITTAL

HOUSE OF REPRESENTATIVES,
COMMITTEE ON SCIENCE AND ASTRONAUTICS,
Washington, D.C., July 31, 1959:

Hon. OVERTON BROOKS,
Chairman, Committee on Science and Astronautics.

DEAR MR. CHAIRMAN: I am forwarding herewith for committee consideration a report on "Space Propulsion", prepared by staff consultant Lt. Col. Paul B. Schuppener, in consultation with Dr. Charles S. Sheldon II, technical director, and reviewed by other members of the professional staff.

This report is based on testimony obtained in both open and executive session hearings before the full committee, and on information obtained through staff research. It summarizes highlights of the testimony and offers conclusions and recommendations on the conduct of the overall space propulsion program.

It is particularly appropriate to take note of the outstanding presentations made by the 27 witnesses representing civilian and military agencies of the Government, private industry, research institutions and universities. These recognized experts in the rocket propulsion field provided technical information so new, so expertly prepared, as to make the record of hearings a first-class textbook in the field. Their individual views and recommendations contained in the record of hearings deserve respect and careful consideration.

CHARLES F. DUCANDER,
Executive Director and Chief Counsel.

CONTENTS

	Page
I. Introduction	1
II. Concepts of employment	1
III. Chemical systems	3
Liquid propellants	4
Solid propellants	6
Summary	7
IV. Nuclear propulsion	7
V. Electrical propulsion	9
VI. Exotic systems	11
VII. Conclusions	12

CONTENTS

		Page
I.	Introduction	1
II.	Concepts of energy	1
III.	Chemical systems	3
	Liquid propellants	4
	Solid propellants	6
	Summary	7
IV.	Nuclear propulsion	7
V.	Electrical propulsion	9
VI.	Exotic systems	11
VII.	Conclusions	12

SPACE PROPULSION

I. INTRODUCTION

Propulsion is the key to space travel. Although many technical elements must be combined to build a successful space ship, without propulsion they are nothing. Electronics, inertial sensing devices, air supply, shielding against radiation, communications, and many other things also need strong support to hasten their refinement. But the key role of propulsion is illustrated by the frustration the United States has felt in the last 2 years. We have had a capability to build a host of beautifully miniaturized instruments and devices, and have shown a broad capability to meet the challenges of a new technological age. Yet most of our satellites have been compared with grapefruit, and could do only so much. In contrast, whether or not the Soviet Union made the most of its opportunity, it did at least have the opportunity to put even thousands of pounds of payload into Earth orbit. For a solar orbit, the 13.4 pounds of our Pioneer IV greatly limited our opportunities, as contrasted with the reported 796 pounds of instruments, or 3,245 pounds of orbiting body of the Soviet Mechta.

It was in the face of this acute problem that the Committee on Science and Astronautics decided to hold exploratory hearings on the problems of space propulsion, to provide itself and the lay public with a better understanding of the magnitudes and the potentials. As a result some eight sessions were held, at which witnesses appeared from appropriate branches of Government, the military, private industry, research institutes, and universities. Their testimony not only provided a wealth of accurate and up-to-date technical information at a level understandable to the layman, but demonstrated that there is general agreement among the most eminent individuals in the field on what constitute essential elements of a space propulsion program. This report is intended to serve as a summary of their views. Readers are urged to study the record of hearings on Space Propulsion conducted by the House Committee on Science and Astronautics, which has been printed as a separate document.

II. CONCEPTS OF EMPLOYMENT

Before going into a discussion of the status and capabilities of the various methods of space propulsion, either currently available or under development, it may be well to discuss some of the more common terms and important concepts of employment.

Military missile systems, from which our basic space capabilities are derived, employ chemical propulsion systems. These include solid propellant rocket motors and liquid propellant rocket engines. (Motor and engine are used interchangeably, but motor is more often

used in connection with solid propellants and engine in connection with liquid propellants.)

Chemical propulsion systems utilizing both solid and liquid propellants will continue to be of prime importance for missiles developed in the defense program. Each of the armed services is carrying on a vigorous research program designed to improve materially the performance of liquid propellants. The Advanced Research Projects Agency of the Department of Defense is sponsoring a diversified and well-funded program to improve the performance of solid propellants (Project Principia). Improvements in fuels and oxidizers for missile propulsion systems will automatically redound to the benefit of space propulsion.

For the next few years, propulsion systems required for unmanned space probes and satellites will employ chemical fuels and a number of engine stages. Thrust units will be of either liquid or solid propellant types, depending primarily upon the factors of reliability, performance, and cost. Designers of upper stages, in which solid propellants are now frequently employed, are turning to liquid engines employing storable propellants in order to retain the same ease of high altitude start and yet gain the flexibility of changing the thrust level and the ability to start and stop a number of times. When nuclear propulsion systems become available, their first usage will probably be for upper stages of these space vehicles.

As current planning goes, it is possible that the first manned flights to the Moon—and later to other planets in our solar system—will originate from space platforms already in Earth orbits some 300 nautical miles above the Earth. A technical decision accepting or rejecting this concept must be made soon. It will take into consideration the difficulty of arranging space rendezvous between a space platform and space vehicles as contrasted with the problem of putting together a single vehicle large enough to proceed directly from the Earth. This is under study in Project Suzano of ARPA.

The particular altitude of 300 nautical miles was chosen because of several basic factors. First, it is above the sensible atmosphere. This provides assurance that the space platform will remain in orbit. Secondly, it is below the Van Allen radiation belt and therefore is safe for personnel. Most importantly, it results in a 96-minute orbit about the Earth, or 15 orbits in a 24-hour period, thus greatly simplifying tracking by Earth stations. Manned space vehicles departing from such an Earth-orbit platform will at least initially employ chemical propulsion systems for relatively short flights, such as to the Moon and return. Longer flights with very large payloads, such as to Mars or Venus, will probably wait until nuclear or electrical propulsion systems become available.

In the discussions of chemical, nuclear, and electrical propulsion systems which follow, it is helpful to bear in mind three bases of comparison of these systems. Each form of propulsion possesses unique advantages for a specific use when compared to others.

The first basis of comparison is total thrust. Though it is difficult to make a precise correlation, the thrust rating of a rocket motor may be considered analogous to the horsepower rating of an automobile. Chemical propulsion systems consisting of both single and clustered liquid rocket engines are now under development and are designed

to provide a total thrust of up to 1½ million pounds. By clustering the 1½-million-pound single chamber engines now under development, it appears feasible to obtain a total thrust of approximately 6 million pounds or more. Initially, technical problems will limit nuclear engines to 100,000 pounds or less thrust, but there is no basic reason why greater thrust ratings cannot be achieved in time. Electrical propulsion systems, when developed, will provide exceedingly low total thrust. Initially, electrical propulsion systems will provide thrust on the order of one-quarter pound. Eventually, they may provide a thrust capability of the order of 1 to 10 pounds. From examination of these total thrust ratings it is apparent that the chemical propulsion systems retain an overwhelming advantage for use in boosters.

A second basis of comparison of chemical, nuclear, and electrical propulsion systems is the performance of the fuel employed. Barring a major chemical breakthrough, such as being able to harness the energy of recombination of free radicals, it appears that fuels and oxidizers employed in chemical propulsion systems will have an ultimate capability of producing on the order of 425 pounds of thrust for each pound of fuel and oxidizer burned each second. This measurement of performance is called specific impulse. Liquid fuels and oxidizers in current common use have a specific impulse of 266 pounds per pound per second. Solid propellant fuels are somewhat lower in specific impulse. Nuclear propulsion systems of the type now under consideration will have a capability up to perhaps three times that of chemical propulsion systems, ranging from 800 to 1,200 pounds per pound per second, and this rating may be capable of further increase, provided much higher temperature materials or new methods of containing the nuclear element are found. Electrical propulsion systems enjoy tremendous advantage in performance, having a capability of 10,000 pounds or more per pound per second specific impulse.

A third factor which must be considered in choosing a propulsion system for space use is the ratio of thrust to weight of the engine. This is the number of pounds of thrust per unit of engine (plus propellant) weight. Chemical propulsion systems have a ratio of approximately 100, nuclear 30, and electrical propulsion systems are way down the scale with a thrust-to-weight ratio as low as 1/10,000. On the basis of this factor, chemical and nuclear rockets, which produce high accelerations or high thrust per unit of weight, again qualify for consideration for booster and soft landing applications. On the other hand, electrical propulsion systems not only produce low total thrust but are extremely heavy due to the weight of nuclear reactor, shielding, and equipment for conversion of heat energy to electrical energy, and therefore produce very, very low thrust per unit weight. They are not capable of lifting a missile off the ground. This low ratio of thrust to weight is, however, overcome by other advantages for certain applications discussed later.

III. CHEMICAL SYSTEMS

We are wholly dependent upon chemical propellants now and it seems highly improbable that space propulsion systems better than chemical will become available for general use in much less than 10 years. Furthermore, we have by no means exhausted possibilities of

44005—59——2

improving chemical propellants. Energy increases up to 50 percent over conventional chemical rocket fuels are theoretically possible.

Chemical propulsion is based upon chemical reaction in which gases and large quantities of heat are liberated. Generally speaking, there are two types of reaction to be considered in the design of propulsion systems—*combination* in which two elements or compounds such as hydrogen (H_2) and oxygen (O_2) are combined to form water (H_2O) and heat energy, and *decomposition* of a more or less loosely bonded compound such as hydrogen peroxide (H_2O_2) into water plus oxygen plus heat energy. The energy (specific impulse) obtainable from a chemical propellant is measured in terms of pounds of thrust resulting from the burning of 1 pound of propellant in a rocket motor or engine in 1 second under specified conditions of chamber pressure and pressure of the atmosphere into which the gases are exhausted. Another way of looking at specific impulse is to remember that it is directly proportional to the velocity of the jet emerging from the rocket nozzle.

Liquid propellants

Liquid propellants, as a group, have widely differing characteristics. Liquid oxygen (LOX) and liquid fluorine, as oxidizers, and liquid hydrogen, as a fuel, are common examples of cryogenic liquids which can be used in liquid rocket engines. The term "cryogen" literally means refrigerant; however, it has been applied to fuels and oxidizers which must be kept cooled to very low temperatures or carefully insulated because of the great rapidity with which they boil away at normal temperatures. (For example, the boiling point of LOX is minus 297° F., liquid fluorine minus 305° F., and liquid hydrogen minus 423° F.) Specific impulses of combinations employing some of these cryogens are high. For example, the theoretical specific impulse at sea level and 500 p.s.i. chamber pressure of liquid oxygen (LOX) and kerosene (RP) is of the order of 266. With liquid hydrogen and liquid oxygen this could be raised to 345. If we could find a way of preventing ozone (this is an oxygen molecule with an extra atom—O_3) from decomposing, we could reach a specific impulse of approximately 375 pounds per pound per second. Increased chamber pressures during burning could bring this efficient propellant combination to more than 400 pounds per pound per second.

Development work on engines utilizing liquid oxygen and liquid hydrogen is now active. While the high energy capabilities of liquid hydrogen as a fuel were demonstrated as early as 1946, anticipated costs of producing and difficulties in storing and transporting have acted as deterrents to its use. A liquid hydrogen propulsion feasibility program begun in 1955 has demonstrated that liquid hydrogen can be produced economically (as low as 10 cents per pound) and stored and transported safely. Development of a liquid hydrogen fueled engine is a straightforward engineering problem requiring 1 or 2 years' effort. Such engines are particularly attractive for use in upper stages where the greatly increased specific impulse of the liquid hydrogen-liquid oxygen combination will, as a rule of thumb, double the payload capabilities for each stage utilized, as compared with presently available engines. A specific impulse of 345 pounds per pound per second is obtainable at sea level, and at the altitudes at which we will use these engines it becomes more than 400. In the latter part of 1958 the Advanced Research Projects Agency announced

the award of a contract for the development of such an engine. Effective July 1, 1959, this project, known as Centaur, was transferred to the National Aeronautics and Space Administration.

Storable propellants are also very attractive to the designer of propulsion systems for use in upper-stage engines. Storables possess the advantage of not boiling away, as do the cryogens, and they can be started and stopped at will. They do not deteriorate during normal periods of storage and they are not excessively corrosive in their action on materials in the tanks, tubing, and valves used to contain them. They may, therefore, be stored in ready-to-fire missiles for appreciable periods of time. It appears possible to obtain storable propellants which will approach the specific impulse of over 265 pounds per pound per second. Nitrogen tetraoxide, as an oxidizer, and hydrazene, as a fuel, are examples of an oxidizer-fuel combination classed as storable.

Some liquid rocket propellants are hypergolic, in addition to other characteristics; that is, spontaneous ignition occurs upon contact of fuel and oxidizer. While this characteristic makes them more hazardous to handle on the ground, it is also advantageous for some space missions.

Still another type of liquid propellant which is valuable for certain uses is the monopropellant. A monopropellant is a chemical compound which in the presence of a catalyst, or with the input of a small amount of initiating energy, decomposes to form heat and gases. Unfortunately, the specific impulse of usable liquid monopropellants is not high, and they are used primarily in cases where ease and reliability of starting and stopping overweigh the disadvantages. For example, those Earth satellites employed for communication and weather purposes which must remain in rather precise orbits may be maneuvered by means of small jets using monopropellants such as hydrogen peroxide or ethylene oxide. Some engineers believe monopropellants can be used in general applications in ways that their comparatively low specific impulse can be more than offset by other savings, but their enthusiasm is not generally shared.

Up to this time liquid propellant systems have predominated in the large missile field and are destined to continue to play an important role in space programs. There are a number of reasons for this. Most significant of them are:

(*a*) Liquid propellants provide the highest specific impulse obtainable today.

(*b*) Due to the regenerative cooling of the rocket motor chamber, long duration firings are attainable. This has the important advantages of minimizing acceleration loads, and makes it worthwhile to seek recovery techniques permitting reuse of engines.

(*c*) Liquid engines can be throttled. This provides more flexibility for control and guidance requirements.

(*d*) Liquid engines can be started and stopped in flight. This capability has advantages for many space applications.

(*e*) Liquid propellants in current use are cheap. For example, liquid oxygen costs approximately 1 cent per pound, and RP, a form of kerosene, 2 cents per pound.

Certain of these advantages, coupled with the experience gained from intermediate range ballistic missiles and intercontinental ballistic missiles utilizing liquid engines, have dictated choice of

liquid propellants for the two large engine developments now underway. The first of these, the Saturn project, is a Department of Defense project which calls for the clustering of currently available liquid engines to form a booster unit capable of producing one and a half million pounds of thrust. Because this project is based upon the use of existing engines, it will begin static testing in late 1959 and will have an early operational capability. Another liquid engine development underway is intended to provide a single chamber engine of new design and capable of producing one and a half million pounds of thrust. It has been initiated by the National Aeronautics and Space Administration and is presently scheduled for approximately 4 years of development effort.

Solid propellants

Solid propellants are of two basic types. The first of these, the so-called double-base propellant, has been known and used in rifles, shotguns, and cannon for over 60 years. Double-base propellants are formed by the mixing of nitroglycerin and nitrocellulose, and when used as rocket propellants may be given additional energy with powdered metals such as aluminum or boron. Double-base rocket propellants continue to be valuable for many purposes, but for others they have been supplanted by the case-bonded, composite, solid propellants developed near the end of World War II by the Jet Propulsion Laboratory under Army sponsorship. Composite propellants are not single compounds but consist of an intermixed fuel and oxidant. Most of these latter propellants are based on ammonium perchlorate in one form or another, mixed with some kind of fuel binder into a liquid mixture which is cast directly into the rocket motor case. After a few hours of curing, the slurry becomes a tough, plastic solid which is bonded strongly to the walls of the motor.

Major problems encountered in the use of solid propellants have been lack of precision in termination of burning, lack of ability to control the direction of thrust, and inability to modulate or throttle. Solid propellants also have lower specific impulse than liquid. However, there is confidence among experts in the field that solid propellants will continue to find application for space propulsion. They enjoy such advantages as—

(*a*) high degree of reliability,
(*b*) simplicity of fabrication of the complete motor,
(*c*) ruggedness and ease of handling and shipping,
(*d*) instant readiness for firing, and
(*e*) great material density. This has the advantage of permitting a smaller vehicle for the same payload.

As high energy propellants and new liquid engines become available for upper stages, solid propellant motors probably will have difficulty in remaining competitive; but improvements in specific impulse, new techniques for rapid termination of thrust, throttling and control of direction of thrust will continue to make them attractive as boosters for many space uses. There has also been a reduction in the weight of motors through development of improved, lightweight, glass-reinforced plastic cases. There are proposals to overcome the 80,000-pound total weight and 12-foot diameter physical size limitations imposed by load-carrying capacities of highway and railroad bridges and clearances of underpasses and obstructions along rights-of-way.

One method would be to ship by air, but a novel idea proposes assembling the motor case or chamber on site and mixing and casting of the propellant as well. With this method, the size of solid propellant rocket motors is almost unlimited. A contract has been let for the design study of a 1½ million pound thrust solid propellant booster. Large motors prepared in this fashion could be fired within a few hours after manufacture or they could be stored, ready for use within minutes after a decision to fire.

Summary

In summary, liquid chemical propellants have greater specific impulse and greater versatility. They will, on the whole, supplant solid chemical propellants for upper stage use, but solids and liquids will remain in active competition for use in large boosters. Reliability, performance, and cost will be the factors upon which a choice between the two will be made. Liquid propulsion systems may gain some advantage with respect to cost if current efforts to develop techniques for the recovery and reuse of large liquid engines prove satisfactory. NASA's Project Scout, a new solid propellant satellite launching system, however, offers its own advantages of simplicity and low cost for lofting moderate payloads.

IV. NUCLEAR PROPULSION

"When we leave the chemical propulsion systems for nuclear and electrical systems, we are going largely into unmapped territory." So stated an important industry witness in his appearance before the Science and Astronautics Committee. He went on to point out that some of the principal problems can now be recognized, but that any program for utilization must necessarily be long range and that specific problems remain to be recognized. However, he and other witnesses appearing before the committee on the subject of nuclear propulsion were confident that we would ultimately obtain this new means of space propulsion. The time estimates ranged from 5 to 10 years, with a consensus favoring 10 years.

As envisaged by most of the witnesses, a nuclear propulsion system would consist of a more or less conventional nuclear reactor which would be used to raise the temperature of liquid hydrogen from minus 423° F., convert it to a gaseous state, and expel it at temperatures from 2,500° F. to 4,000° F. This high-temperature hydrogen gas would then be expanded through a nozzle to produce a high velocity jet and thereby thrust. The principal departure from a chemical propulsion system lies in the utilization of a nuclear reactor to provide heat energy instead of obtaining it through chemical reaction. Specific impulses on the order of 1,200 pounds per pound per second would be obtainable at the higher temperatures. This is approximately three times as great as the highest specific impulse obtainable through chemical reaction. Even the lower operating-temperature reactors producing a specific impulse of 600 to 800 pounds per pound per second may represent sufficient improvement to be of interest. Project Rover, a national program to develop a nuclear engine, is based on this heat exchanger concept of propulsion. As a step in the Rover concept, the Kiwi–A test reactor was operated late this spring in Nevada.

The caution expressed by most witnesses as to an early completion of a nuclear rocket engine certainly seems justified by a consideration of some of the principal engineering problems to be solved. For example—

(*a*) Reactor controls must be made capable of bringing the reactor safely up to operating power within a matter of seconds.

(*b*) Methods must be provided to reduce heat from neutron and gamma radiation in adjacent engine components and propellant tanks. Radiation shielding is also a problem to limit induced radioactivity in adjacent structural elements.

(*c*) Consideration must be given to the fact that fission products will be carried by the propellant into the exhaust jet, producing considerable radioactivity in the surrounding area.

(*d*) Reactor materials will be required to operate at very high temperatures without erosion, corrosion, or change in physical characteristics.

The major problem in obtaining the high efficiency possible with nuclear propulsion lies in the development of suitable materials to withstand the extreme operating conditions. The peak performance of a heat-exchanger type of rocket is fixed by the ability of core materials, moderators and reflectors, and structural components of the engine to withstand thermal stress, radiation damage, and corrosion and erosion. The attainment of a safe, reliable engine of high power is dependent upon gaining new knowledge of the properties of materials. It may be necessary to develop new alloys or ceramics to meet the stringent requirements. However it is considered possible to develop an engine which operates at lower temperatures, and therefore lower efficiency, using presently available materials.

During the 12-year period from 1945 to 1957, in spite of our best efforts in the great metallurgical laboratories of the country, we were able to increase the working temperatures at high stresses of metal alloys and ceramics only 300°, from approximately 1,500° F. to 1,800° F. This suggests the magnitude of the problem faced.

High temperatures are not the only problem encountered. We want to use hydrogen because of its low molecular weight, but hydrogen embrittles some materials, forms hydrides with others (with resultant corrosion) and forms volatile hydrogen compounds with others (thus eroding the material). Resistance to corrosion and erosion and ability to withstand high temperatures are not enough to qualify a material for nuclear engine use. Materials must also be able to withstand high stress imposed by temperature change and thrust loading. In some cases a material otherwise qualified for use may fail because it is not dimensionally stable under continued neutron bombardment or undergoes other changes in physical properties. A great amount of work is going on to determine and tabulate the properties of a large number of materials under conditions of high temperature and high stress, in the presence of corrosive and erosive substances and exposed to heavy neutron bombardment. For example, elements such as graphite, tungsten, tantalum, molybdenum, niobium, rhenium and zirconium are under careful investigation. In many cases carbides, nitrides, and borides of these and other elements possess even better properties, and these, too, are being examined. Much work remains to be done and progress will certainly not be easy unless an unforeseeable breakthrough occurs.

Rewards for the solution of nuclear energy problems are great. For example, a theoretical mission of lifting a 50-ton payload from Earth to orbit around Mars and return to an orbit around the Earth, if done with a high-energy chemical propulsion system, would require a six-stage vehicle and a thrust unit capable of lifting 30 million pounds. On the other hand, if this same mission were to be undertaken with a nuclear-powered vehicle, only two nuclear stages would be required and the thrust unit would be required to lift only 3 million pounds.

While the main objective is to provide nuclear space propulsion, important corollary advantages will undoubtedly accrue. Solutions to many of the problems confronting us will result in far better nuclear powerplants for commercial use.

V. ELECTRICAL PROPULSION

The tongue-twisting word "magnetogasdynamics" (or magnetohydrodynamics—MHD for short), is applied to an area of research and development into how electrostatic and electromagnetic fields may be used to accelerate plasmas, ionized gases, and colloidal solutions to extremely high velocities (up to 300,000 miles an hour) and exhaust these materials as a jet to obtain propulsive thrust. Before discussing the many different types of electrical propulsion systems which have been proposed, it would be well to describe plasma, ionized gases, and colloidal solutions.

When energy in the form of heat is transferred into a metal, the material first becomes liquid; then it passes to a vapor state, and ultimately it is brought to such a state of excitation that one or more of the dynamic electrons which surround the nucleus are shaken loose. The remaining molecule—less electrons—is now known as an ion and carries a positive electrical charge equal but opposite to that of the departed electrons. The freed electron, or electrons, represent negative charges. If after ionization there is no separation of the atoms, ions, and electrons, the resulting mixture is known as a plasma. If the temperature is carried high enough, such as in a thermonuclear reaction, all atoms would be ionized and the plasma would consist only of ions and electrons.

There are several ways of producing the heat necessary to obtain ionization. One is to cause the vaporized material to flow through a suitable nozzle and impinge on a hot surface, perhaps made of tungsten, producing contact ionization. Another method of ionization is to expose the material to a high-temperature electric arc. Materials suitable for consideration as ionizing propellants are the alkali metals such as cesium, potassium and sodium. Cesium, because of the ease with which an electron may be dislodged, is the favorite theoretical propellant.

The plasma, having been produced by electrical means, may either be allowed to expand through a type of nozzle to produce thrust as is the case in a conventional chemical rocket, or the plasma may be further accelerated by being passed through an electromagnetic field. In the latter case, extremely high specific impulses are obtained. Plasma temperatures far exceed the capabilities of engine structural materials and therefore electromagnetic fields may be employed to contain the plasma and to serve the purpose of a nozzle in directing jet flow.

If the ions and electrons are extracted from the plasma and separately accelerated, either by passing through an electrostatic field only or through both electrostatic and electromagnetic fields, the device is known as an ion engine. The electrons by themselves furnish little propulsive thrust, but it is necessary to expel them in order to keep the entire rocket system electrically neutral.

Still another engine of the electrical type employs an electrically charged liquid colloid and operates at lower temperatures. The colloid consists of electrically charged particles so small that they remain in suspension or distributed throughout the liquid carrier.

Of the electrical engines described, ion engines appear more advanced and have reached a working stage of development. Plasma engines were described by some witnesses as being in an earlier stage. The charged colloid system also shows promise and was stated to have fewer serious problems to overcome. All these electrical systems show promise in principle, but there is an obvious need for more research on fundamental magnetogasdynamics before the value of this form of propulsion can be assessed properly. From the testimony provided to this committee, it appears that relatively inefficient versions may be developed in as little as 5 years but in view of the serious problems more sophisticated and greater thrust models will probably take as long as 10 years.

All forms of electrical propulsion systems which have been proposed have one formidable underlying problem—power supply. A typical ion or plasma engine needs 200 to 300 kilowatts per pound of thrust. Ion and plasma engines may be developed to produce as much as 10 pounds of thrust. Some idea of the magnitude of these power needs can be drawn from a comparison with an average U.S. residential city of 10,000 persons. Such a city requires approximately 970 kilowatts of electrical capacity. Furthermore, in order that electrical propulsion systems can be utilized for the purposes to which they are best adapted, that is, space travel, say, to Mars and return, or the positioning of communication and weather satellites, the powerplants must be capable of continuous operation with an extremely high degree of reliability for many days at a time over a period of a year or more. The simple fact is that we do not now have reliable, lightweight powerplants meeting these criteria. A more or less conventional nuclear reactor used to heat a fluid which would drive a turbine, and the turbine in turn an electrical generator, has been proposed as one solution to power needs. The capability to place a powerplant of this type into a small package of relatively light weight and yet to retain reliability in continuous operation over a long period of time seems highly speculative at this time. Three other methods of producing electrical power appear to offer promise. One is to produce electricity directly by thermionic means, that is, devise an efficient conversion of heat to electricity in a nuclear reactor by "boiling" electrons out of a metal. Still another method proposed is a thermoelectric conversion using the difference in electrical potential which exists between two metals at different temperatures. A third method suggested would pass a gas ionized by nuclear means through a magnetic field to generate electricity. AEC's Project Snap is studying some of these and other possibilities, but with emphasis on auxiliary power requirements.

Faced with the obstacles of difficult technical problems, requirements for a large amount of money, and somewhat doubtful success far in the future, why should we pursue the development of electrical propulsion systems? The answer is that for such a use as long "freight" hauls deep into space such a system promises to be most economical. The fuel efficiency promised, long duration of operational capability and low thrust level also are exactly what we need for positioning of satellites designed to execute precise orbits such as the 24-hour communication satellite which, in order to perform its function, must remain fixed with respect to a point on the Earth. Weather satellites impose similar criteria. Other military satellites designed for reconnaissance purposes, orbiting perhaps 65 miles above the surface of the Earth, could be kept in orbit and perform their mission most efficiently by utilizing electrical propulsion systems.

It must be emphasized that electrical systems show no capability for use in take-off or landing on any of the planets. Electrical systems will have great usefulness for going from one orbit to another or for precise positioning in a required orbit and where duration of operation is long.

VI. EXOTIC SYSTEMS

Space propulsion systems discussed under the heading of chemical, nuclear and electrical are either in operational or developmental use or have been demonstrated in principle in the laboratory. The search for better means of space propulsion does not stop with these more or less conventional ideas. Numerous proposals for more exotic systems have been advanced.

One such proposal, which is reasonable in theory but so far has proved impracticable to devise, is a propulsion system based upon the use of free radicals. It represents a several-magnitude jump of specific impulse in a chemical propulsion system, because specific impulses theoretically attainable range from 1,000 to 1,500 pounds per pound per second. This tremendous release of energy results from the recombination of a molecule which has been caused to break apart by heat or by other means. For example, free hydrogen exists in a stabilized form only as diatomic hydrogen, or H_2. However, if hydrogen molecules forced to split to form monatomic hydrogen can be stabilized to remain so under storage conditions, their recombination in a rocket engine combustion chamber would provide a specific impulse potentially as high as 1,500. The problem is maintaining monatomic hydrogen in that state. Supercooling or mixing with inert gases are two possible approaches.

Another type of nuclear propulsion system which has been proposed for 10 years or more is the gaseous reactor or "fizzler." This involves the intimate mixing of the propellant and gaseous uranium and the separation of the uranium from the propellant before expulsion from the rocket. Such a gaseous fission reactor would necessarily operate at extremely high temperatures—above the vaporization temperatures of materials of interest. A thermonuclear system has also been proposed, but the problem of containing temperatures approaching those of the sun probably places this device many years into the future.

Another idea, which has progressed to the point where the Advanced Research Projects Agency in the Department of Defense has let a

million-dollar feasibility study contract, is in the field of controlled nuclear detonations. This project proposes to examine a new method for achieving massive propulsion through the detonation of a series of small nuclear devices. It might lift a space platform weighing as much as 1,000 tons. This is Project Orion.

Another space propulsion proposal would take us back many centuries in time to the use of sails for propulsion. Very simply, it proposes that a vehicle literally sail through space, utilizing a solar sail consisting of a large area of thin plastic material coated with a microscopically thin coating of a metal such as aluminum. The solar sail would be unfurled after the space vehicle had been placed in Earth orbit far outside the atmosphere. The pressure of solar rays (photons) on the surface of the sail would provide a small but inexhaustible accelerating force. More complex forms of photon propulsion have been suggested by scientists as a means of traveling from one solar system to another. This may be possible, but at this time we know so little about the conversion of matter into radiant energy and the focusing of this energy for propulsion purposes. Also, it is recognized that travel close to the speed of light, even if attainable, might pose many other acute problems, such as the high energies which would be attained in a relative sense by any scattered particles in space, bombarding with deadly gamma rays the spaceship and its occupants.

Popular literature and even some serious research have been concerned with entirely new approaches to travel through space, such as use of anti-gravity or the creation of gravity screens. Our best understanding of physical laws today seems to preclude any of these approaches to control of gravity as workable; however, no one can predict what new forces or scientific laws may be discovered in the future.

Perhaps the most imaginative idea of all involves the charting and utilization of plasma or energy belts in space. Such an energy belt exists around the Earth. A considerable amount of knowledge of this phenomenon was gained as the result of experiments designed by Dr. Van Allen of Iowa State College with instrumentation in several Explorer satellites. By judicious navigation from one such energy belt to another, it may some day be possible to cruise almost indefinitely on free space fuel.

Whether or not any of these novel ideas are ever brought to practical use, their existence at least demonstrates the interest and wide range of activity in the field of space propulsion.

VII. CONCLUSIONS

This report began with the statement, "Propulsion is the key to space travel." This is also a proper conclusion. Hearings before the House Science and Astronautics Committee, during which some 27 individuals representing expert opinion in industry, the National Aeronautics and Space Administration, and the Department of Defense, demonstrated that the problems of space propulsion now are being vigorously attacked in many aspects. In retrospect, some of these efforts began too late and, even now, some of the problems are so vaguely defined that we do not realize how much effort is required for solution. It is possible, then, that such problems may not be getting the kind of attention they deserve and require.

With quite good reason, space propulsion programs can be divided into two categories, those which are achievable in the very near future—say 5 years—with the application of straightforward engineering techniques, and a second category in which we may merely see the problems better defined in 5 years and begin to see solutions in 10 years.

In the case of the first grouping, there are vigorous and well-defined efforts on the part of the individual military services and the Department of Defense to improve the chemistry of liquid and solid propellants. Theoretically, improvements in the energy-carrying capabilities of chemical propellants can be as great as 50 percent. These programs must continue to be supported with great vigor because they represent the most tangible efforts we have to date of improving the fuels for space propulsion.

It is now obvious to all that had we instituted a strong program for the development of large rocket engines at the close of World War II when we had great but untapped capabilities, we would not now be in a position of second place to the U.S.S.R. so far as "weightlifting" capability is concerned. But this is past, and now we must do our best to make up for lost time. Saturn, an Advanced Research Projects Agency project for the development of a 1½-million-pound booster employing a cluster of existing and proven liquid rocket engines, is designed to give us a tremendously improved space capability within the next few years. It must be given full support if we are to maintain a balanced and yet increasing rate of effort in space activities. Anything less will keep us in a position inferior to the Soviets.

Still another large rocket engine project is somewhat further off in time, but one which logically follows the Saturn project. This is the National Aeronautics and Space Administration development of a single chamber liquid rocket engine capable of producing 1 to 1½-million pounds of thrust. This project represents a reasonable extension of effort based upon experience we have gained with rocket engines produced for such missile programs as Atlas, Jupiter, Thor, and Titan. The NASA project is scheduled for completion in approximately 4 to 6 years. A test version has already produced over a million pounds of thrust, briefly. It will enable us to make another big jump in propulsion capability, because we can reasonably expect that this large engine will be formed into a cluster arrangement for a booster which will be capable of producing over 6 million pounds of thrust. This concept is employed in the proposed Project Nova system.

With the increasing size and complexity, and above all, cost of the very large propulsion systems, it behooves us to practice every reasonable economy. One such economy may be the development of techniques which will permit the recovery and reuse of large rocket engines, once they have performed their task and have been jettisoned. Investigations for several recovery techniques are currently underway and the results will be applied to some of our current programs.

One of the most immediate and pressing requirements is for the development of upper stage liquid rocket engines utilizing high energy propellants such as liquid oxygen and liquid hydrogen, or storable propellants. At least three such engines, ranging in thrust capability from 10,000 pounds to 300,000 pounds are a "must" if we are to make efficient use of the large boosters which exist today or are under

development. It is possible, for example, to increase payload capabilities from 2 to 10 times merely by substituting high energy upper stage engines for those now used. The Advanced Research Projects Agency has in the past few months contracted for the development of a second stage engine of this type. The project, known as Centaur, was recently transferred to the National Aeronautics and Space Administration.

Nuclear propulsion and electrical propulsion fall into the second category, programs which are perhaps 10 years off in time, and are largely dependent upon how much progress we are able to make in research. One important aspect of this is research on materials. We know, for example, that pure metals, alloys, and ceramics which we have been able to devise permit operating temperatures on the order of 1,800° F. Nuclear reactors, if they are going to be efficient enough to carry into space, must be capable of material operating temperatures of approximately 2,500° F. and preferably 5,000° F. or more in order to gain efficiency. Compare this goal with the present capability of our earthbound nuclear powerplants which operate at less than 1,000° F. and in which, for the present, we are content to seek modest gains of 10 to 20 percent in performance. There are other problems in connection with materials, such as ability to withstand stress, effects of neutron bombardment on physical properties, and others; but this single example of temperature limitation points up a tremendous need for materials research. If there is one area of basic research which needs greater emphasis, it is perhaps this. Project Pontus of ARPA is one effort designed to solve some of these materials problems.

When we lick the research problem, nuclear reactors will provide us with a means of carrying heat energy into space; but we have other important energy needs. Electricity is needed for instrumentation, for guidance, for communication, and for propulsion. Simple, compact, reliable, lightweight electrical systems capable of producing up to 300 kilowatts of electricity continuously for a year or more simply do not exist. They must be brought into being before we can venture far into space and before we can devise truly efficient Earth satellites such as we can now recognize a need for, and are developing for communication and weather purposes. At one end of the scale of electrical requirements where power needs are small, direct conversion from solar energy may be feasible. However, at the far end of the scale—300 kilowatts or more—conversion from the heat of a nuclear reactor is probably the answer.

It is difficult to maintain a proper perspective in the appraisal of the overall space propulsion program. The vast and exciting capabilities promised by nuclear, electric and other exotic systems tend to color our thinking. It is too easy to forget that perhaps years of research, followed by development and extensive testing, are required before these new systems can reach the degree of reliability we have even now in our missile propulsion systems. Reliability cannot be bought with money alone. It is acquired and proven through experience. The years of research, development, testing, and the billions of dollars which have gone into guided missiles are now the most valuable asset of our national space program. Manned flight into space awaits only the refinement of reliability in these systems. If we are to make real progress in space exploration and use in the next several years we

must stress component improvement and build bigger thrust units for space use based upon reasonable extensions of our missile propulsion system experience. Nuclear, electrical, and perhaps other systems seem assured, but are necessarily years into the future, particularly insofar as manned space flight is concerned.

Problems in the space propulsion field touch upon almost every aspect of science and technology. They range from conventional chemical combustion processes through advanced nuclear technology to unanswered questions on the formation of the universe. Their solution will not only give us the means to travel in space, but will improve and enrich our lives on Earth.

○